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REVIEV ARTICLE

Spatiotemporal Characteristics and Trend of Puting Beliung Across the Indonesian Archipelago

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Abstract. Puting beliung (PB), or small-scale tornado, is a significant and under-researched extreme weather phenomenon in Indonesia, often causing severe damage to infrastructure and posing risks to public safety despite their brief localized nature. Therefore, this research aimed to examine spatial and temporal patterns and trends of PB events across Indonesia from 2011 to 2024, applying statistical analysis, geospatial mapping, and the Mann-Kendall trend test to a database of 2,434 PB events. The results showed that PB events primarily cluster in western and central regions, specifically on Java Island, and the highest frequencies were observed in East Java, West Java, and Central Java. These events typically occur in low-lying zones (0–500 meters above sea level), affecting agricultural and residential land in flat terrain. Temporally, most PB arises in the afternoon (1:00–3:00 pm local time), with peak frequencies in January, March, and November, coinciding with Indonesian monsoonal and transitional seasons. A trend analysis shows a statistically significant nationwide yearly increase of approximately 12 PB events, with 8 provinces exhibiting notable upward patterns. When compared to other PB-prone nations, Indonesia records a higher annual PB frequency than Japan, Australia, and Bangladesh, but remains well below the United States. The novelty of this research lies in its long-term, nationwide dataset and thorough spatiotemporal assessment, providing the first comprehensive examination of PB trends at national and provincial scales in Indonesia. These results provide crucial insights for disaster risk mapping, mitigation strategies, and early warning systems.

1. Introduction

Indonesia has abundant solar radiation and water vapor from its surrounding waters, creating favorable conditions for the development of rainfall-producing clouds (Wijayanti et al., 2021). These atmospheric conditions can potentially trigger significant weather phenomena, such as high-intensity rain, strong winds, hail, and puting beliung (PB). Subsequently, PB, as the local Indonesian term for small-scale PB, is defined as a rotating air column originating from Cumulonimbus (Cb) clouds that touches the ground surface, with a minimum velocity of 34.8 knots or 64.4 km/hour and occurs in a brief duration (BMKG, 2010). According to data from the National Disaster Management Agency of Indonesia (BNPB, 2024), extreme weather phenomena, including PB, heavy rainfall, and high winds, rank second among the most extreme weather events in Indonesia from 2020 to 2024. This extreme phenomenon is frequently associated with a similar but more intense and broader-scale phenomenon, namely PB (Mujiasih et al., 2014; Yulihastin, 2023). The physical characteristics of PB include funnel-like shapes (Nurjani et al., 2013; Rusmala et al., 2022; Siswanto & Supari, 2012) or spiral formations (Harsa et al., 2011; Nurlambang et al., 2013), circular motion (Nikmah & Hazim, 2023), with straight-line trajectories (Rizal et al., 2012).

PB events are concentrated on Java Island (Darman, 2019; Nurjani et al., 2013; Nurlambang et al., 2013), accounting for approximately 56% of cases (Lee et al., 2017). As the most densely populated region in Indonesia, this area faces an elevated threat to public safety. In contrast, Kalimantan and Papua Islands are considered relatively safe from this phenomenon (Nurjani et al., 2013). Temporally, PB events predominantly occur during midday and afternoon hours, specifically between 12:00–16:00 local time, with seasonal peaks in March and October annually (Nurjani et al., 2013). It is also reported that areas with dense green vegetation and low temperatures have low PB potential, while regions with sparse vegetation and high air temperatures show higher PB potential (Rahardian & Ruslana, 2022).

According to research by Ali & Hidayati (2016), there was an increase in PB events in Indonesia from 2011 to 2016. This trend is in line with research by Tippett et al. (2016), which reported a positive trend in the number of strong PB during toutbreak periods, numerous PB events connected to the same synoptic-scale system (AMS, 2012), in the United States. Several factors are suspected to trigger this frequency increase, including climate change (Henson, 2021; Woods et al., 2023), land-use changes (Rahardian & Ruslana, 2022), population growth (Fan et al., 2023), and others.

Although PB occurred within narrow spatial and temporal scopes (Aliftha et al., 2020), its impacts can be severely destructive (Cahyanti et al., 2017; Fernanda et al., 2024; Nurjani et al., 2013; Rizal et al., 2012). The reported impacts generally include building damage, fallen trees, and casualties (injuries and fatalities). Nurlambang et al. (2013) documented the destructive effects of this phenomenon, reporting a total of 425 fatalities, 3,867 injuries, and 51,978 severely damaged houses from 1977 to September 2013. In Central Java Province, PB events caused losses of IDR 280.835 billion (Nurjani et al., 2013). Meanwhile, PB events in Rancaekek District, Bandung, West Java, on February 21, 2024, affected 835 families, injured 33 people, and caused minor to severe damage to 534 buildings (Saputra, 2024). Psychological impacts, including trauma and anxiety in children, were also reported by Nikmah and Hazim (2023) among PB victims in Sidoarjo, East Java, necessitating psychological interventions such as Psychological First Aid (PFA).

According to the Intergovernmental Panel on Climate Change (IPCC, 2021), trends in extreme phenomena caused by convective systems, such as hail and PB, exhibit low confidence due to non-uniform monitoring and reporting systems. While previous research on PB events in Indonesia generally focused on micro- and mesoscale meteorological analysis, spatial and temporal analysis, and risk assessment, there is a need for more comprehensive investigations emphasizing detailed spatiotemporal analysis using long-term and recent data. This research addresses these needs by analyzing the spatiotemporal patterns and trends of PB events in Indonesia over the past 14 years, constrained by the availability of historical data. The results are expected to contribute to the scientific understanding of PB or small-scale tornado spatiotemporal characteristics in tropical island regions and PB trends in Indonesia. Utilizing observational data enhances global understanding of extreme weather phenomena, particularly PB events, by providing valuable insights and supporting existing research. The results will provide data-based information to strengthen early warning systems and support hydrometeorological disaster mitigation and adaptation programs, specifically focused on PB phenomena in Indonesia.

2. Methods

This research covers the entire Indonesian region, extending from 90°E to 141°E, over a period from January 1, 2011, to December 31, 2024. PB events dataset includes temporal information (date and time), spatial parameters (province, city/district, sub-district, village, geographical coordinates), and impact data. This data was sourced from Darman (2019) for the 2011-2014 period, from the Ministry of Health (Kemenkes, 2016) for 2015-2016, and from the Indonesian Agency of Meteorology, Climatology, and Geophysics (BMKG, 2024) for 2017 through December 2024. Additionally, this research utilizes Indonesian geospatial data, including elevation, slope, and land cover from the Geospatial Information Agency (BIG, 2024). The duration was selected based on the availability of PB frequency data in Indonesia, while data validation was conducted by cross-referencing event records with extreme weather data from BNPB.

Statistical calculations of PB frequency at the national scale, provincial scale, and by different periods (yearly, seasonal, monthly) were conducted using simple statistical calculations with the following definitions:

1. The total number of PB events was calculated by summing all recorded occurrences in specific periods (annual, seasonal, monthly) or regions (national, provincial).
2. Seasonally, periods are defined as DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), and SON (September-October-November). This classification was selected to obtain analytical results not only for wet and dry seasons but also for transitional periods.

Geospatial analysis was performed using ArcGIS Desktop version 10.6.

Trends in PB frequency in the research period (annual, seasonal, and monthly) were analyzed using the Mann-Kendall test (Cao & Cai, 2022) at both national and provincial scales, using Equations 1 through 5 as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\,(x_j - x_i) \quad (1)$$

Where:
S = Mann-Kendall statistics
n = number of data points
x_j , x_i = sequential data values

The sign function is defined as:

$$\text{sign}\,(x_j - x_i) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{t=1}^{m} t_t(t_t-1)(2t_t+5)}{18} \quad (2)$$

Where:
Var (S) = the variance of S
q = the number of tied groups
t_p = the number of data values in the pth group

The standardized test statistic Z is computed as:

$$Z = \frac{S-1}{\sqrt{Var(S)}} \; if \; S > 0 \quad (3)$$

$$Z = 0 \; if \; S = 0 \quad (4)$$

$$Z = \frac{S+1}{\sqrt{Var(S)}} \; if \; S < 0 \quad (5)$$

A positive Z value indicates an increasing trend, while a negative Z value shows a decreasing trend. The null hypothesis of no trend is rejected at significance level α if $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal distribution table.

3. Results and Discussion

The results of this research are categorized into three distinct components: (1) spatiotemporal PB frequency analysis, (2) geospatial analysis, and (3) frequency trend analysis in the Indonesian region.

3.1 Spatiotemporal Pattern of PB Frequency in Indonesia

During the research period, 2,434 PB events were recorded in Indonesia, averaging 174 events per year. The average number of PB events per year varies significantly across different regions, including Japan (20-30 events/year), Australia (60 events/year), Bangladesh (6-7 events/year), China (100 events/year), Africa (17 events/year), Europe (181 events/year), and the United States (1200 events/year) (Bai et al., 2019; Grieser & Haines, 2020; Inoue et al., 2011; Masum, 2020; Milford & Goliger, 1994; Tippett et al., 2016; Zovko-Rajak et al., 2023).

PB occurred in all provinces of Indonesia, as shown in Figure 1, although with varying frequencies across regions. This phenomenon is concentrated in the western and central parts, from Sumatra to Sulawesi, but primarily on Java Island. Spatial pattern of PB across major islands (Sumatra, Java, Kalimantan, Sulawesi, and Papua) shows considerable variation, ranging from low to high frequency. In contrast, smaller archipelagos such as Riau Islands and Nusa Tenggara exhibit relatively low frequencies. The top five provinces for PB events are East Java (N = 436, 18%), West Java (N = 328, 14%), Central Java (N = 316, 13%), South Sulawesi (N = 168, 7%), and North Sumatra (N = 136, 6%).

The results are in line with investigations by Darman (2019), Nurjani et al. (2013), and Nurlambang et al. (2013), which identify Java Island as the area with the highest frequency of PB. This is consistent with research conducted by Supari & Siswanto (2012), which indicates that natural disasters caused by natural hazard phenomena occur with high frequency on Java Island. It is important to note that natural hazards do not cause natural disasters alone; disasters materialize when these hazards occur in areas with high vulnerability (Firmansyah et al., 2019). Other regions with significant PB frequency were observed in Aceh, North Sumatra, and South Sulawesi.

The analysis of total PB frequency across Indonesian provinces during 2011-2024, displayed in Figure 2, exhibits a remarkable spatial distribution that correlates with population distribution across the archipelago. Provinces on Java Island dominate PB events records, with the highest numbers from East Java (446 events), West Java (333), and Central Java (323), significantly higher than both the national annual average (174 events) and provincial average (72 events). The high density of PB reports in Java aligns with its population distribution, as the island is home to 55.85% of Indonesia's total population while occupying only 6.75% of the country's land area, resulting in an exceptionally high population density of 21,944 inhabitants per square kilometer (BPS, 2024).

The gradient of PB frequency from West to East is highly correlated with population gradients, with western regions of Indonesia (specifically Java and Sumatra) accounting for approximately 77.65% of the national population, in contrast to merely 3.2% in the eastern parts, which includes Maluku-Papua (BPS, 2024). This spatial correlation suggests a significant population bias in PB reporting, as documented in research showing how areas with higher population densities typically record disproportionately more PB events than sparsely populated regions (Elsner et al., 2013).

The minimal PB reports in eastern provinces such as Papua (1 event) and Maluku (9 events) likely show not only potential meteorological differences but also significant underreporting due to lower population densities, reduced observation capacity, and less developed infrastructure for monitoring and reporting severe weather events. Similar results were also reported by Darman (2019), Lee et al. (2017), and Nurjani et al. (2013), who found that the three provinces on Java Island showed the highest frequency of PB events.

Figure 3 shows the inter-provincial distribution of PB frequency in Indonesian 34 provinces from 2011 to 2024 at monthly intervals. Java Island represents an Indonesian primary PB hotspot, with East Java consistently recording the most significant numbers, reaching 60 events in 2016 and maintaining substantial frequencies (30–54 events) in several years. West and Central Java follow closely, with comparably high values of up to 47 events (in 2022) and 48 events (in 2019), respectively.

A substantial west-to-east gradient exists, with much of western Indonesia experiencing PB frequencies an order of magnitude greater than East—South Sulawesi, being a notable exception among eastern regions with its consistently modest frequency (15-22 events in peak years). Temporally,

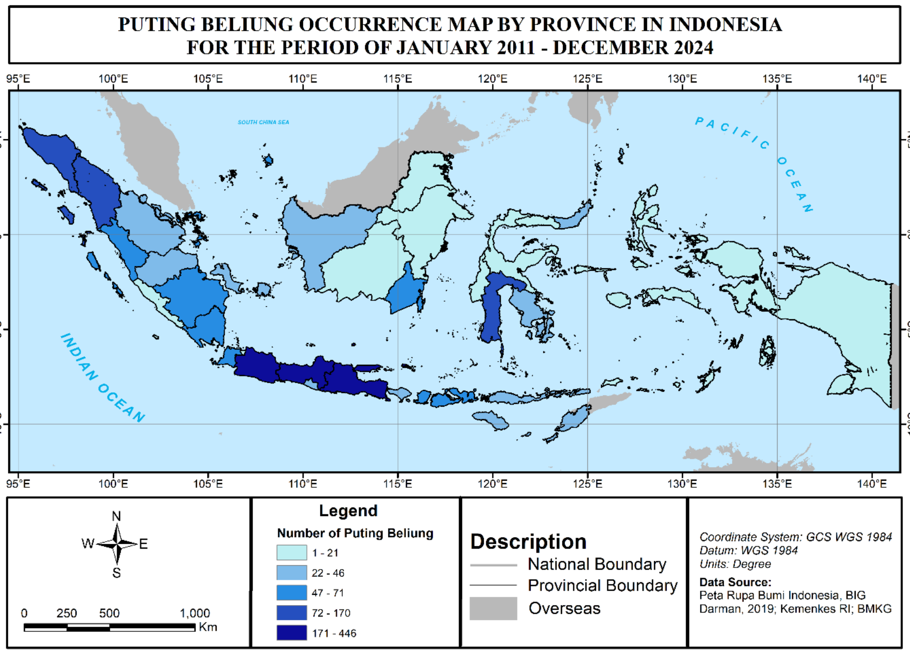

Figure 1. PB Events Map by Provinces in Indonesia for January 2011- December 2024

substantial variation occurs from year to year, with 2015-2019 showing above-average PB activity in many provinces while 2011 generally experienced a dearth of events.

The sharp distinction between densely populated Java (intense red color representing 40–60 events) and sparsely populated eastern provinces such as Papua, Maluku, and North Kalimantan (largely pale-yellow color indicating 0–1 event per year) is striking. Some provincial trends show multi-year patterns, such as the heightened activity in East Java from 2015 to 2019, and a potential increase in West Java, which produced Indonesian peak readings in 2022. The map effectively captures Indonesian PB climatology, highlighting the essential need for locale-specific disaster preparedness plans that address the high spatial variability of PB risk across the archipelago.

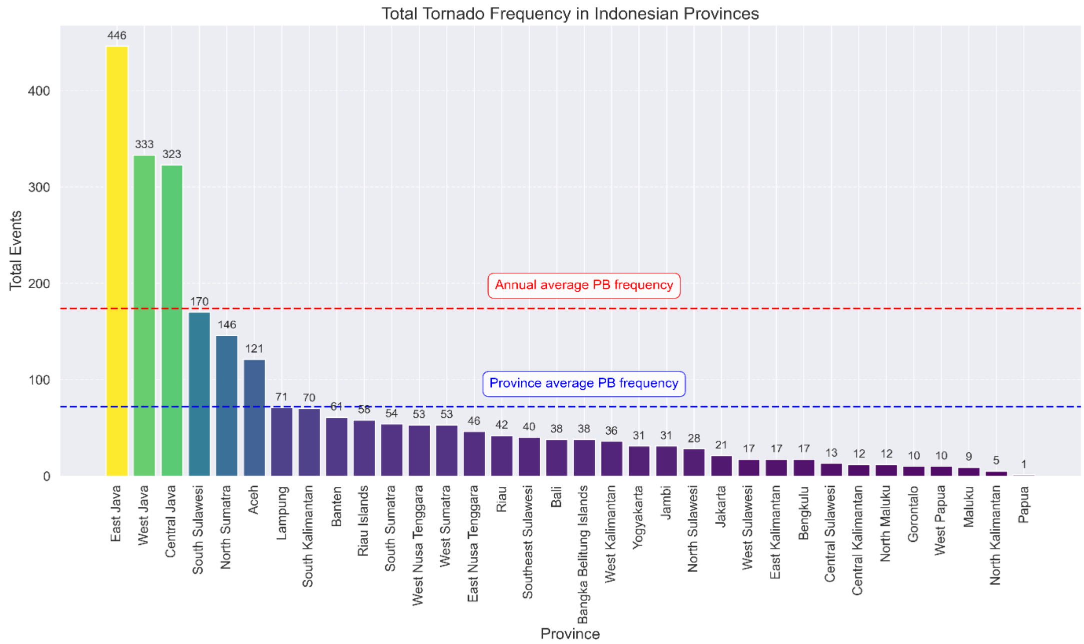

Figure 2. PB Frequency Across Indonesian Provinces During the 2011-2024 Period, the Red Dashed Line Representing Annual Average Frequency, the Blue Dashed Line Indicating Provincial Average Frequency

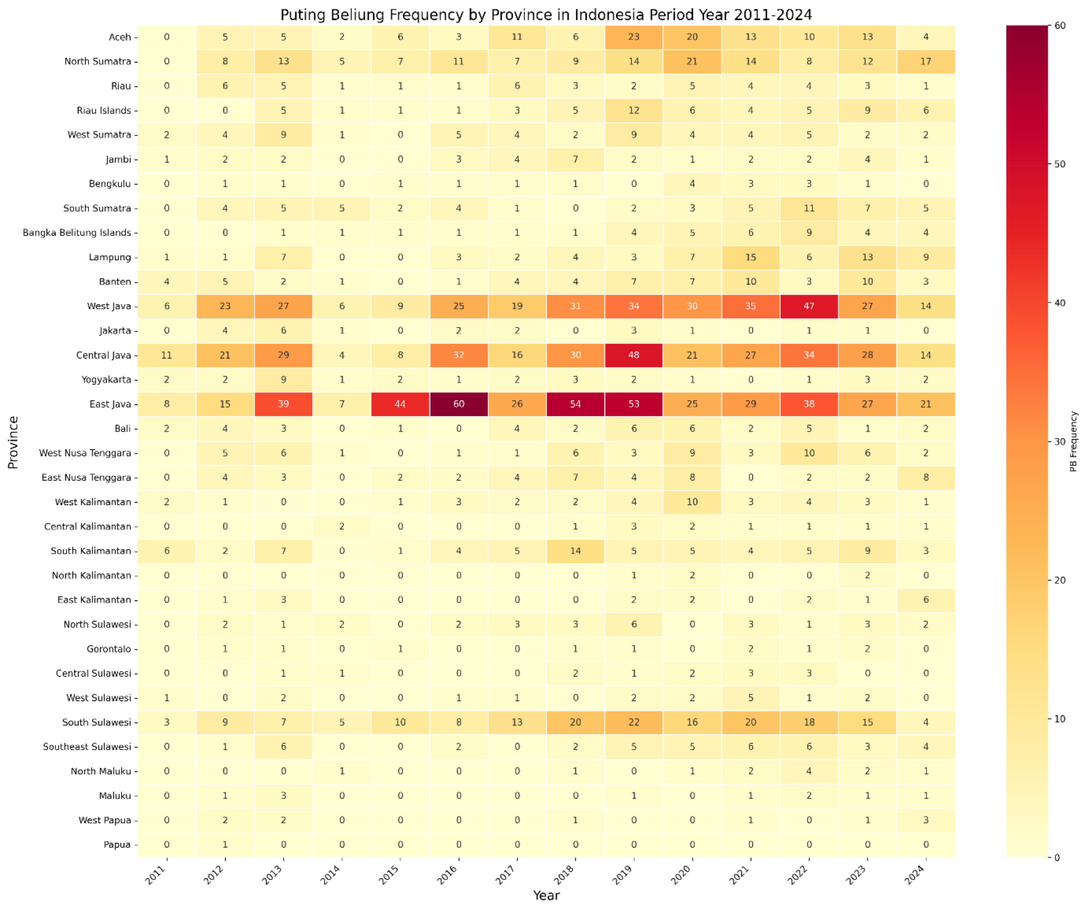

Figure 3. PB Frequency by Province in Indonesia, Period 2011-2024

The spatiotemporal distribution of monthly PB frequency across Indonesian 34 provinces during 2011-2024, as shown in Figure 4, identified significant regional and temporal variations. Provinces on Java Island demonstrate the highest occurrence rates, with maximum monthly counts of 68 in East Java, 56 in Central Java, and 48 in West Java. In contrast, eastern regions such as Papua, North Kalimantan, and Maluku experienced considerably lower PB frequencies, with monthly maximums averaging only 1-2 events.

Distinct monthly patterns are observable in specific provinces. South Sulawesi, West Java, Central Java, and East Java show elevated PB frequencies during early and late months of the year, particularly January, March, and November/December. Meanwhile, Aceh and North Sumatra experience increased PB frequency during mid-year periods, specifically April/May and August/September. These patterns correlate with the predominant rain types in these regions: equatorial in Aceh and North Sumatra, and monsoonal in Java and South Sulawesi. The remaining 28 provinces typically display sporadic and relatively erratic PB event patterns.

These results are consistent with previous research. Lee et al. (2017) identified November as the month with the highest PB events in Indonesia during 2012-2014, while Nurjani et al. (2013) reported the highest PB events occurring from October to March in 2011-2012.

The polar plot visualization of seasonal PB frequency across Indonesian 34 provinces during 2011-2024, presented in Figure 5, shows distinctive spatiotemporal patterns. Java Island represents PB epicenter of Indonesia, as East Java, West Java, Central Java, and Yogyakarta show clear diamond-shaped patterns with relatively high intensities during all seasons, but with significant dominance observed during DJF–MAM. The wet season period in Indonesia with monsoonal rainfall type lasts from November to April, while the dry season lasts from May to October (Mulsandi et al., 2024). The equatorial rainfall type region experiences high monthly rainfall throughout the year, with two wet season peaks in April and November (Direktorat Perubahan Iklim, 2025).

A west-to-east gradient is apparent across the archipelago, with western provinces (Java, Sumatra) experiencing more extended seasonal variability, in contrast to minimal activity observed in eastern provinces (Papua, North Kalimantan). Remarkably diverse seasonal signatures characterize different regional clusters: Sumatra-based provinces (Aceh, North Sumatra, Lampung) show pronounced MAM-DJF dominance; Kalimantan provinces display varied patterns, with West Kalimantan having the most balanced distribution; and Sulawesi shows regional variation with North Sulawesi peaking in DJF-MAM while South Sulawesi exhibits more balanced seasonality.

Several unique provincial signatures stand out—Banten's pronounced MAM orientation, Maluku's DJF preference, West Papua's JJA concentration, and Gorontalo's extremely narrow seasonal window. These patterns reflect Indonesian complex regional climate dynamics, where the interaction between monsoon cycles, local topography, and land-sea temperature contrasts creates vastly different conditions for PB formation across the archipelago.

This seasonal inconsistency in PB events is not singular to Indonesia, as it surfaces differently across an assortment of areas worldwide. Each nation exhibits unique propensities grounded in the geographic and atmospheric traits, with some locales experiencing more frequent twisters in summer, while others witness elevated rotational storm activity in winter. Regional variances interconnect with larger-scale climatological mechanisms to fashion customized tornadic timelines for every location.

In China, PB events are most common during the dry season, in July and August, with an average of 43 events per year (Xue et al., 2023). In South Korea, PB events are most common in summer, between June and August (Lim et al., 2018). In India, it often occurs during the pre-monsoon season between March and June (Bhan et al., 2016). In Africa, the summer season from November to February is the period with the highest frequency of occurrence (Milford & Goliger, 1994). In the United States, PB most often occurs in spring,

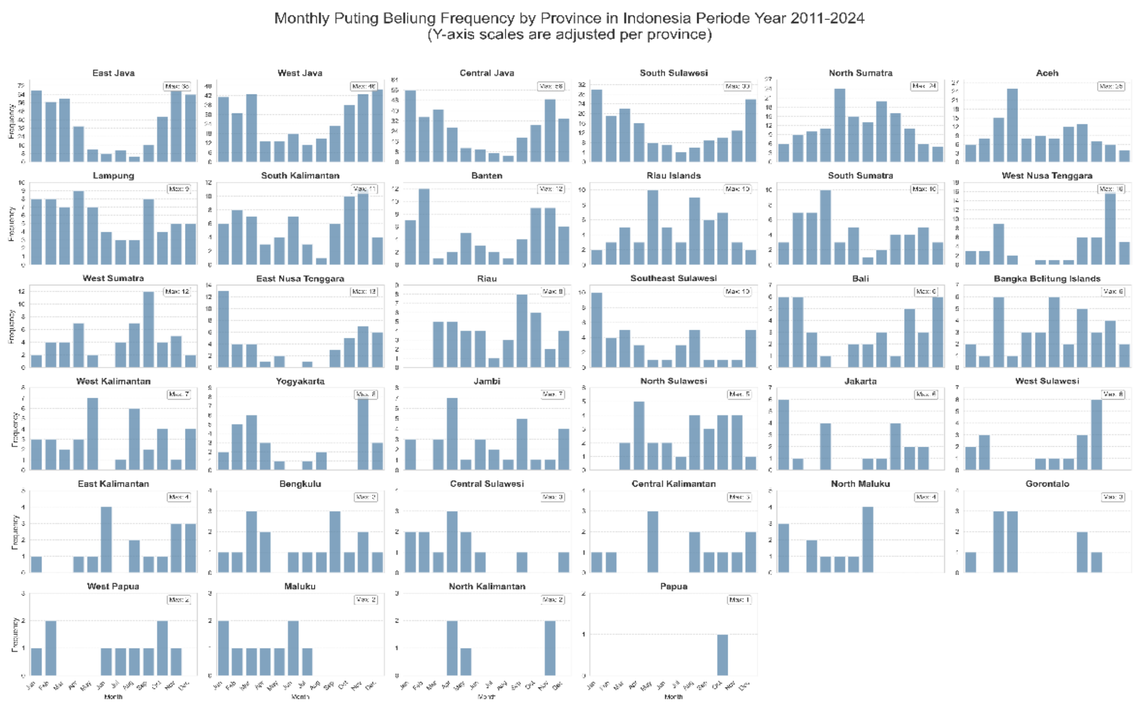

Figure 4. Monthly PB Frequency by Province in Indonesia, Period 2011-2024

between April and June, with an average of up to 1,200 events per year (Tippett et al., 2016). Meanwhile, in South American countries such as Brazil and Argentina, it is most common in spring and early summer (De Lima Nascimento et al., 2014; Vanessa et al., 2022).

The hourly PB frequency distribution analysis across Indonesian 34 provinces, as shown in Figure 6, shows distinctive diurnal patterns that reflect the thermodynamic processes driving PB formation in the archipelago. A pronounced afternoon peak (13:00-15:00 Local Time (LT), red bars) dominates the temporal pattern in most provinces, particularly evident in Java Island, where East Java, West Java, and Central Java record maximum frequencies of approximately 35, 43, and 37 events, respectively, during this period. This afternoon concentration aligns with maximum surface heating, resulting in atmospheric instability that typically peaks in the early to mid-afternoon.

A secondary peak during late afternoon/early evening hours (16:00-18:00 LT, purple bars) is visible in provinces such as South Sulawesi (with approximately eight events) and North Sumatra, suggesting the persistence of convective activity into evening hours in certain regions. Morning hours (07:00-12:00 LT, yellow/orange bars) show moderate activity across several provinces, while nocturnal PB (22:00-06:00 LT, gray/blue/green bars) remains relatively rare nationwide. However, some provinces like South Kalimantan exhibit notable early morning events. Significant regional variations emerge—Java provinces display classic afternoon-dominated patterns with sharp peaks at 13:00-15:00 LT; Sumatra shows more temporally distributed patterns; Sulawesi exhibits strong late-afternoon biases; while eastern provinces such as Papua and Maluku record minimal events overall but maintain the afternoon preference.

The polar chart shown in Figure 7 shows the extensive profile of PB events by time of day over Indonesia during 2011–2024. The visualization reveals a clear diurnal trend with a striking peak in the afternoon, showing that PB in Indonesia exhibits a precise temporal distribution during the day. The statistics indicate the concentration its concentration in the afternoon, with 41% of events occurring between 13:00-15:00 LT, marking the peak of maximum activity, followed by the 16:00-18:00 LT time window, accounting for 27% of cases. These two afternoon timeslots (13:00-18:00 LT) collectively represent a significant 68% of the nationwide PB events, as reported in the figure caption.

The morning period shows light activation, with moderate activity of 9% occurring during 10:00-12:00 LT, while early morning hours (07:00-09:00 LT) account for only 4% of events. Evenings and nights also experience minimal PB activity, with each 3 hours accounting for only 3-6% of the total, the 01:00-03:00 LT period being the least frequent at 3% of events. This result aligns well with Nurjani et al. (2013), who stated that PB during the period 1990-2011 most frequently occurred between 12:00-16:00 LT. Similarly, Darman (2019) reported that during 2011-2014, PB in Indonesia most commonly occurred in the afternoon and evening.

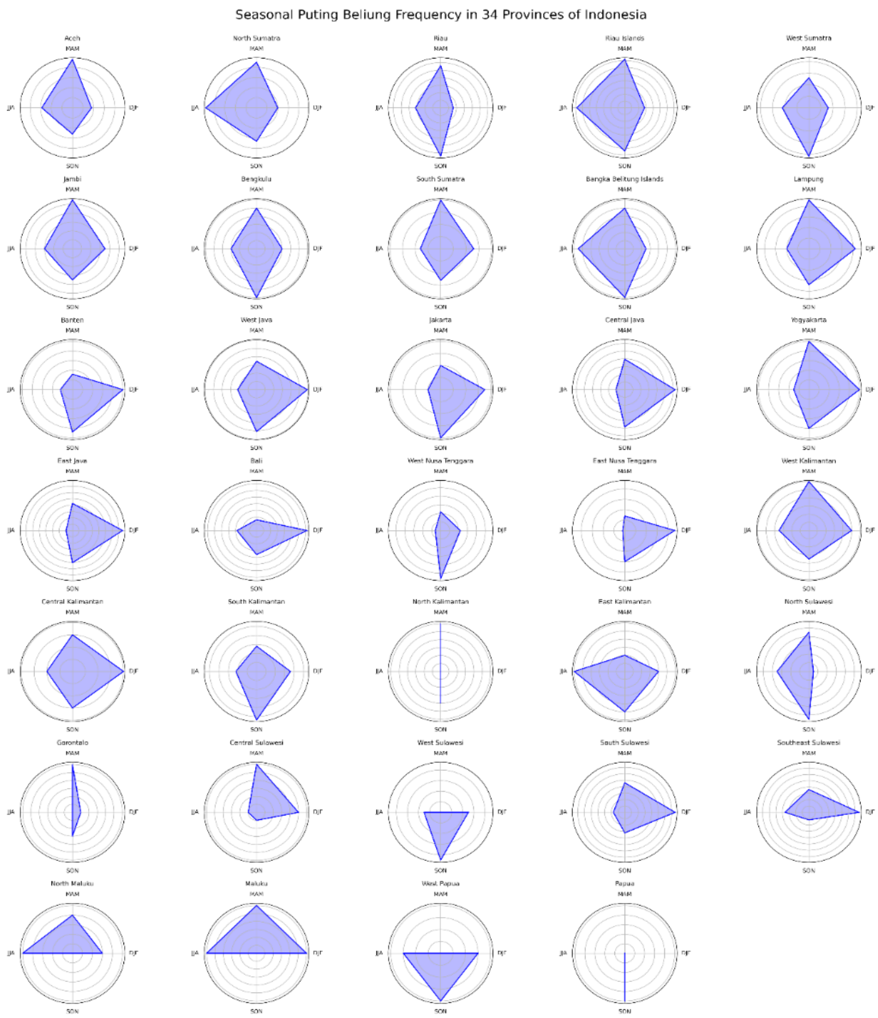

Figure 5. Seasonal PB Frequency in 34 Provinces of Indonesia

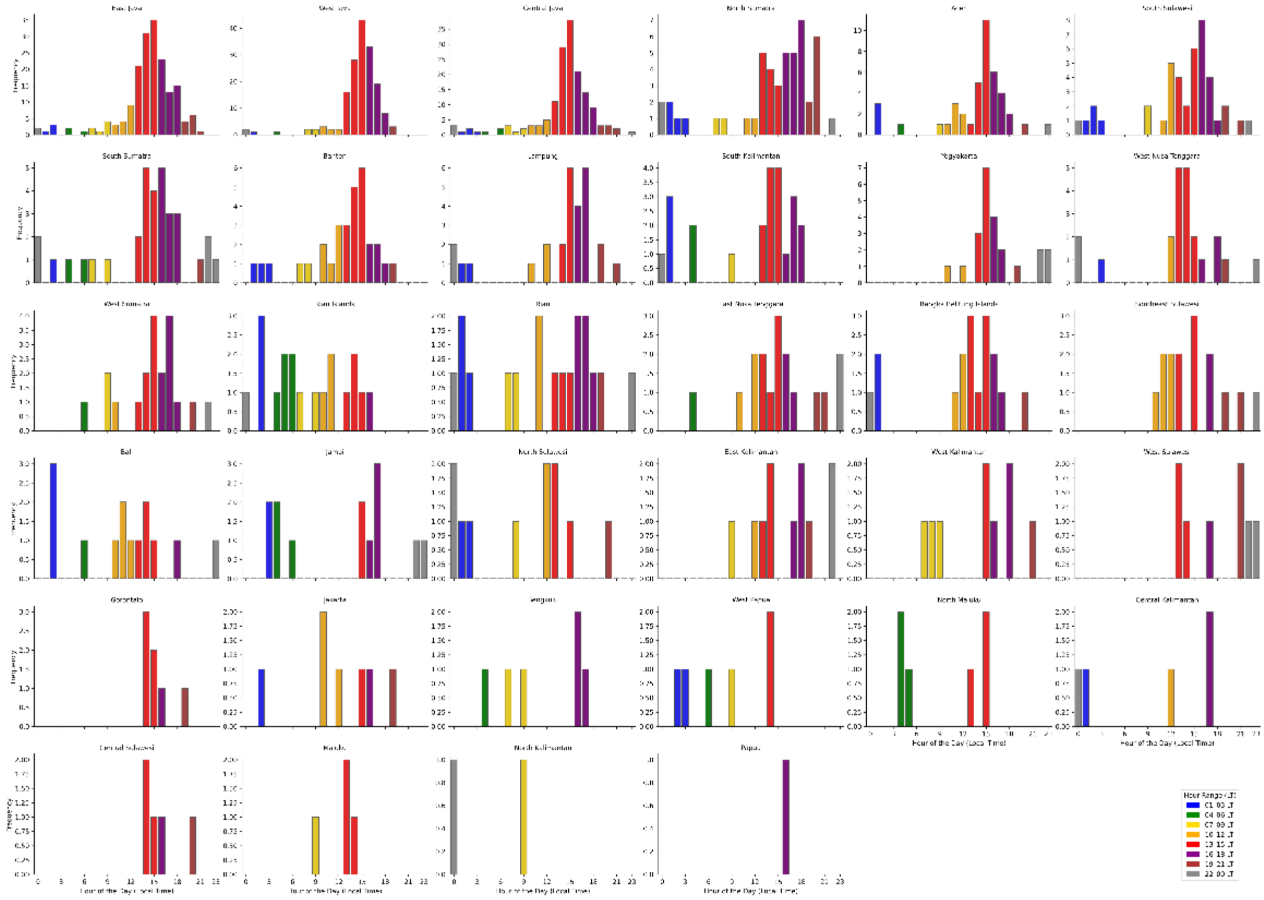

Figure 6. Hourly Distribution of PB Events in Indonesia from 2011 to 2024. The Y-axis shows the Frequency of PB Events, the X-axis shows the Hour of the Day in LT. The Color Bar Represents Different 3-Hour Periods.

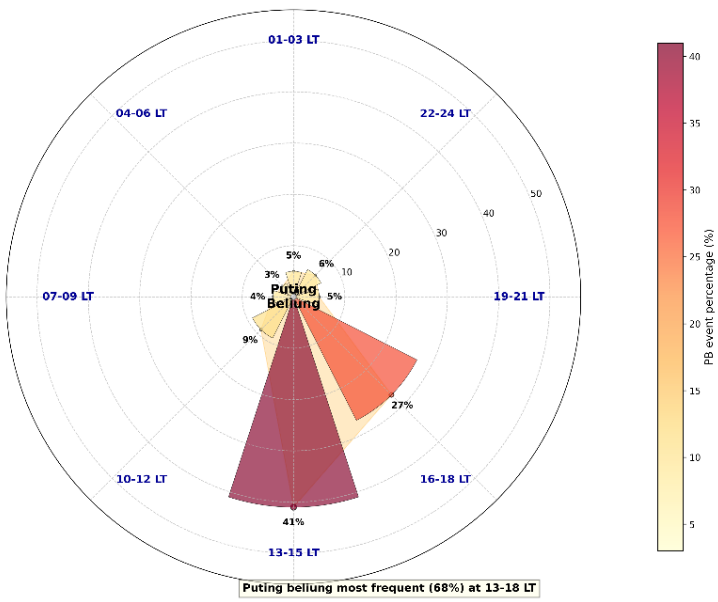

Figure 7. Polar Plot of PB Events in Indonesia by LT for the Period 2011–2024

This unique diurnal signature is consistent with the known diurnal cycle of daytime atmospheric instability in tropical regions, characterized by peak surface heating in the late afternoon and associated with optimal conditions for the initiation of convective storms and PB genesis. The dramatic drop in frequency during the night indicates the stabilizing atmosphere that occurs with nightfall, when solar heating ceases. The visualization effectively illustrates the importance of afternoon vigilance in PB planning across Indonesia, as the majority of activity occurs in a narrow 6-hour afternoon window from 13:00-18:00 LT.

In line with the findings above, this same period, between 13:00-18:00 LT, is when most PB events occur in Europe (Taszarek et al., 2020). Similarly, in Bangladesh, which often occurs in the afternoon and early evening (Masum, 2019), while in India, the afternoon to evening period is the peak time (Bhan et al., 2016).

3.2 Geospatial Aspect Analysis of PB Events in the Top 5 Provinces

A comprehensive geospatial analysis was performed across the 5 provinces exhibiting the highest PB event frequency during the research period. This analysis aimed to investigate the geographical and topographical characteristics of areas susceptible to this extreme meteorological phenomenon. Analysis of PB events distribution points about geospatial aspects such as elevation, land cover, and slope in East Java Province, as illustrated in Figure 8, during the period from 2011 to August 2024, demonstrates a strong correlation with elevation, with the majority of events (381 events, representing 89%) concentrated in areas between 0-500 meters above sea level. Analysis of land use patterns indicates that agricultural areas experienced the highest frequency of PB events (62%), followed by residential and urban zones (24%) and forested regions (12%). The remaining events were distributed across open land, water bodies, and shrubland, each accounting for less than 1% of total events. Regarding topographic characteristics, the distribution strongly favors flat terrain (93% of events), with decreasing frequencies observed on gentle slopes (5%), moderately steep terrain (1%), and steep slopes (0.2%).

The analysis of PB distribution in West Java, as shown in Figure 9, demonstrates that elevation plays a significant role, with 59% of events occurring at elevations of 0-500 meters above sea level and 35% at 500-1000 meters. Regarding land use patterns, settlements and urban areas account for 49% of PB events, while agricultural and forested areas represent 38% and 12%, respectively. Slope analysis reveals a strong preference for flat terrain, accounting for 86% of all recorded events.

Elevation analysis in Central Java demonstrates that a predominant proportion (80%) of PB events occurred at levels ranging from 0 to 500 meters. Analysis of land use patterns indicates that agricultural areas accounted for 65% of PB events, while residential and urban areas comprised 28% of events. Slope analysis shows that the vast majority (84%) of the events were concentrated in flat terrain, with an additional 12% occurring in areas of gentle slope. The detailed spatial distribution is presented in Figure 10.

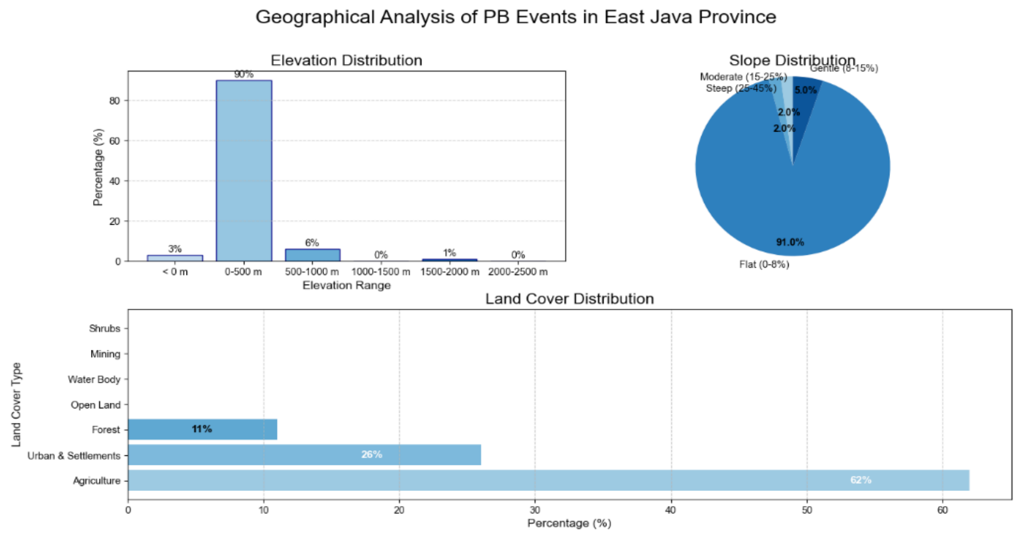

Figure 8. Geospatial Analysis of PB Events in East Java from 2011 to 2024, Showing Elevation (Upper Left), Slope Percentage (Upper Right), and Land Cover (Bottom)

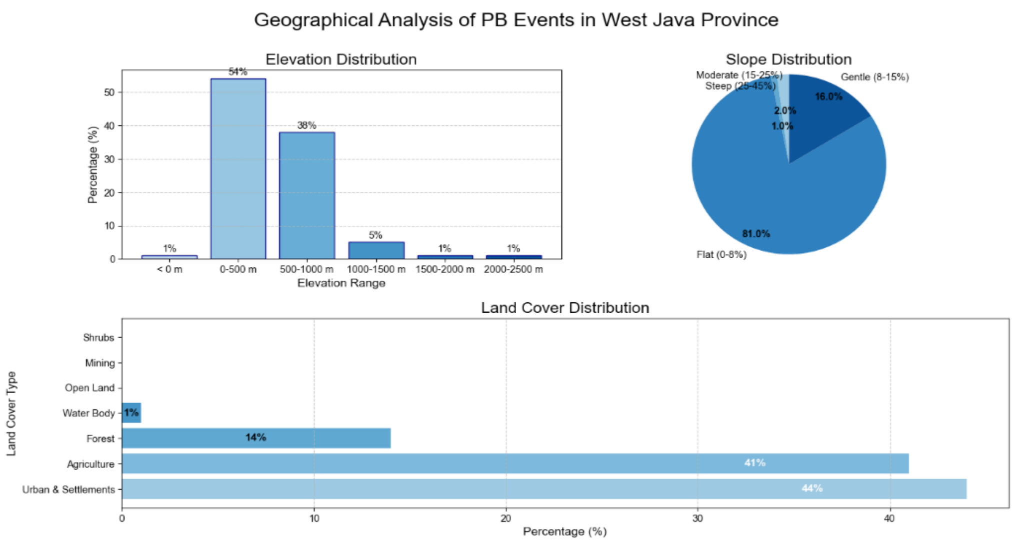

Figure 9. Geospatial Analysis of PB Events in West Java from 2011 To 2024, Showing Elevation (Upper Left), Slope Percentage (Upper Right), and Land Cover (Bottom)

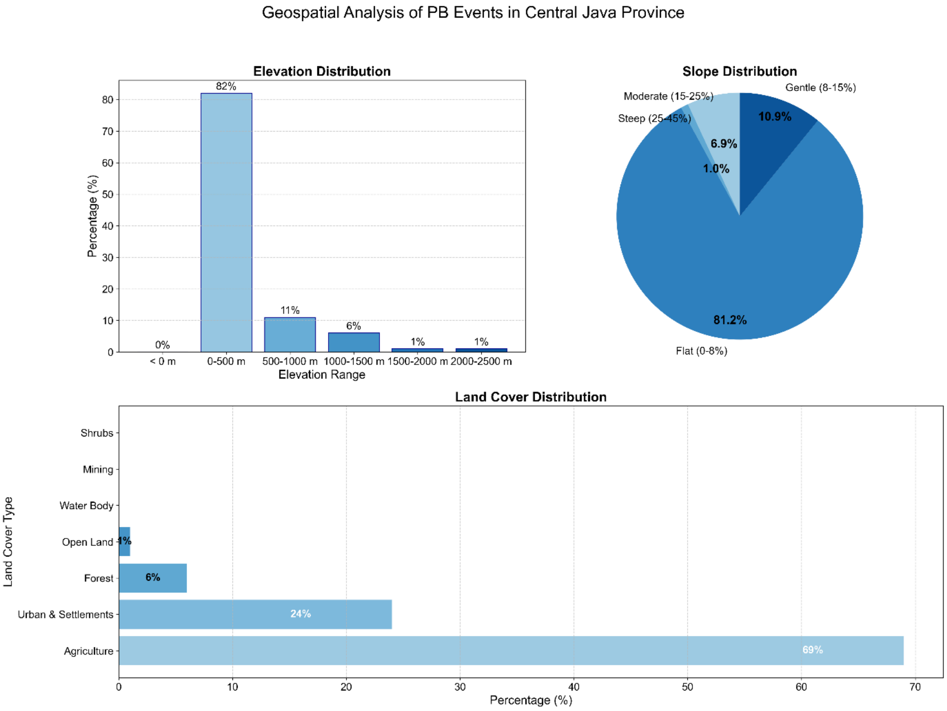

Figure 10. Geospatial Analysis of PB Events in Central Java Province from 2011 to 2024, Showing Elevation (Upper Left), Slope Percentage (Upper Right), and Land Cover (Bottom)

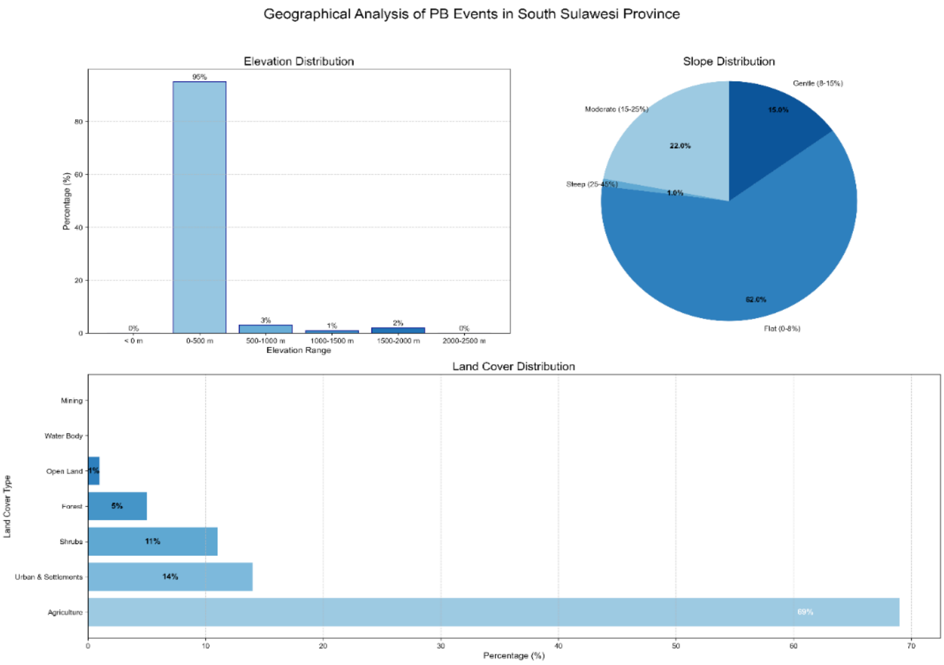

Figure 11. Geospatial Analysis of PB Events in South Sulawesi from 2011 to 2024, Showing Elevation (Upper Left), Slope Percentage (Upper Right), and Land Cover (Bottom)

The spatial distribution of PB events in South Sulawesi (Figure 11) strongly correlates with topographic features. The majority of events (85%) were concentrated in low-elevation areas (0-500 meters), while 9% occurred at higher elevations (1000-1500 meters) and 5% at intermediate elevations (500-1000 meters). Land use analysis indicated a predominant occurrence in agricultural landscapes (73%), followed by shrubland (13%) and urban residential areas (11%). Slope analysis showed that most events occurred on flat terrain (68%), with decreasing frequencies on gentle slopes (17%), moderately steep terrain (9%), and steep areas (7%). These results are in line with research by Syafitri et al. (2021), which reported that the potential incidence of PB events in Sidenreng Rappang District, South Sulawesi, includes flat slopes, with a slope of 0-8%, and the type of land cover of paddy fields.

Figure 12 shows the analysis of PB distribution in North Sumatra Province, where the majority of events (87%) occurred at elevations between 0-500 meters, with smaller proportions at 1000-1500 meters (7%) and 500-1000 meters (4%). Land use assessment showed a predominant concentration in agricultural regions (66%), followed by residential and urban areas (29%). Slope analysis further indicated a substantial prevalence of PB events in flat terrain (88%).

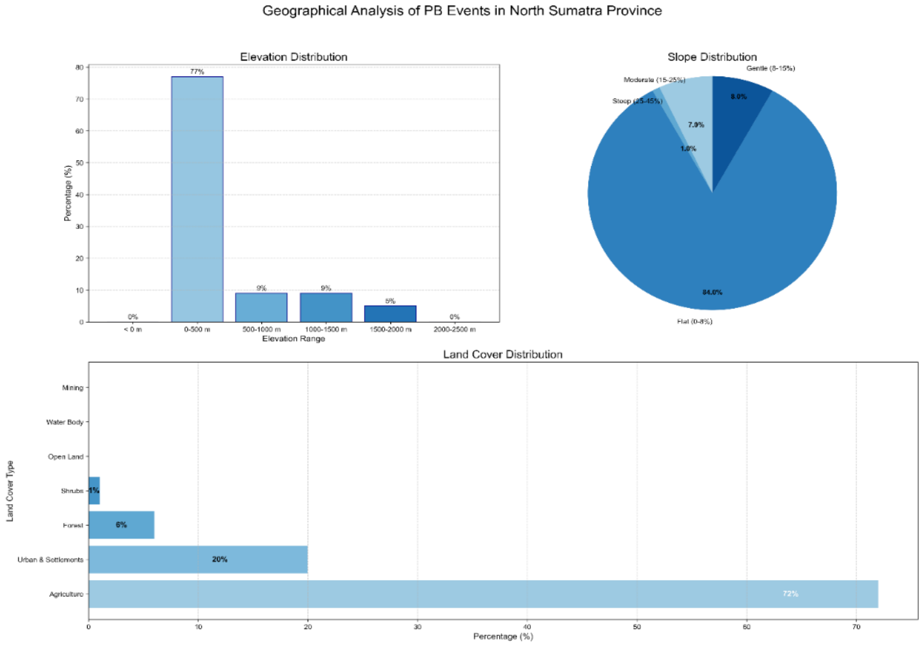

Figure 12. Geospatial Analysis of PB Events in North Sumatra from 2011 to 2024, Showing Elevation (Upper Left), Slope Percentage (Upper Right), and Land Cover (Bottom)

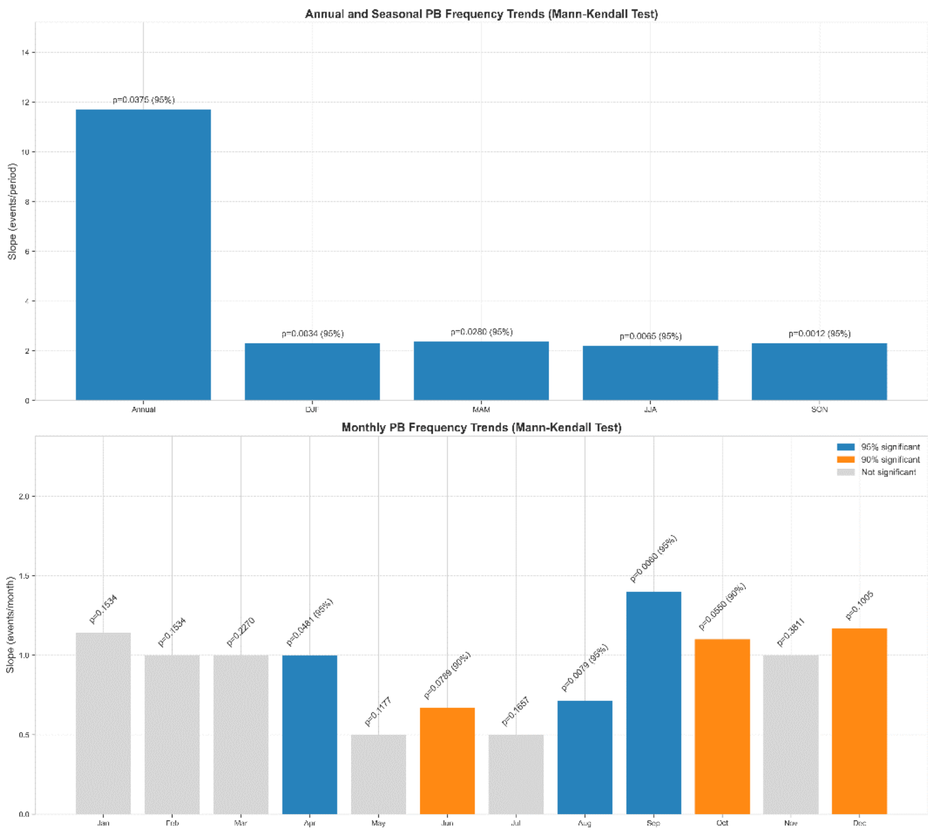

Figure 13. Annual and Seasonal PB Frequency Trends (Above) and Monthly PB Frequency Trends (Bottom) from 2011 to 2024. The Blue Bars Represent Statistically Significant Trends at A 95% Confidence Level, the Orange Bars Indicate Significant Trends at A 90% Confidence Level, the Gray Bars Show Non-Significant Trends. Slope Values Indicate Trend Magnitude.

Geospatial analysis of the 5 provinces that recorded the highest frequency of PB events during the research period showed a tendency to decrease in frequency as elevation increased. The land cover analysis indicates that agricultural lands and settlements/urban areas constitute the dominant land cover types for PB events distribution. Agricultural coverage peaked in South Sulawesi (73%) while showing its lowest value in West Java (37%). West Java exhibits the highest proportion of settlements and urban areas (49%). Forest coverage remains minimal across all provinces, with East Java showing the highest percentage (12%). South Sulawesi shows distinctive characteristics, combining extensive agricultural coverage and substantial shrubland presence (13%). Land utilization for infrastructure, mining activities, and water bodies shows relatively insignificant values.

The terrain slope gradient analysis shows that flat topography (0-8% inclination) demonstrates the predominant frequency of PB events across all 5 provinces, with distribution percentages ranging from 67% to 93%. South Sulawesi exhibits notably higher topographical heterogeneity than other provinces under research. Steep gradient classifications (25%-45%) show statistical significance exclusively in South Sulawesi (6.8%). The data indicate an inverse correlation between slope gradient and PB event frequency.

3.3 Trend Analysis of PB Frequency in Indonesia

Based on data from 2011 to 2024, the results of the Mann-Kendall trend analysis for PB frequency in Indonesia are presented in Figure 13. The x-axis represents different periods, while the left y-axis displays slope values and the right y-axis shows the corresponding p-values. At the 95% confidence level (indicated by blue bars), the annual statistics reveal a strong upward trend, with the highest slope value approaching 12. Several seasonal periods (DJF, MAM, JJA, SON) also exhibit significant increasing trends at the 95% confidence level, with slope values ranging from approximately 2.0 to 2.5. In the monthly analysis, June, October, and December demonstrate increasing trends at the 90% confidence level (orange bars), while April, August, and September show significant increasing trends at the 95% confidence level. The remaining months do not exhibit any significant trends (gray bars).

The results of this research clearly show that in 2011–2024, the frequency of PB events in Indonesia has increased steadily each year, indicating an alarming climate-related trend. Although the magnitude of the increase is less pronounced than the annual trend, all four traditional seasons exhibit statistically significant upward tendencies in seasonal PB frequency. The monthly analysis shows more complex patterns, only certain months-namely April, June, September, and December-show significant upward trends, while most other months show no statistically significant changes in PB frequency.

Trend analysis of PB frequency at the provincial level was conducted using the Mann-Kendall test. Figure 14 shows the spatial distribution of PB frequency trends across Indonesian provinces from 2011 to 2024. Provinces exhibiting a statistically significant increasing trend at the 95% confidence level (shown in blue shades), with maximum slopes of up to 1.5, include Aceh, North Sumatra, Riau Islands, Bangka Belitung Islands, Lampung, West Java, Southeast Sulawesi, and North Maluku. Most other provinces-including those on Java, Kalimantan, Sulawesi, Bali, Nusa Tenggara, Maluku, and Papua-do not show statistically significant trends in PB frequency, as indicated by light gray shading.

China has experienced a reported decline in the number of PB days by 10 per decade, particularly during the summer months (Xue et al., 2023). In contrast, the United States, widely recognized as a global hotspot for PB activity, has exhibited relatively stable national trends in frequency. However, significant spatial variation exists, with decreasing trends observed in the central and southern Great Plains, and increasing trends reported in the Midwest and Southeast regions (Gensini & Brooks, 2018). In Virginia, PB events increased between 1990 and 2019, with annual averages rising to 18 events and 7 PB days per year (Allen et al., 2021). Similarly, Tippett et al. (2016) reported that the frequency of PB event outbreaks has increased, with the most extreme outbreaks exhibiting particularly rapid growth rates.

4. Conclusion

In conclusion, based on spatiotemporal analysis conducted in this research, PB events in Indonesia are predominantly concentrated in the western and central regions of the country, particularly on Java Island. Over the 14 years from 2011 to 2024, a total of 2,434 PB events were recorded, with an average of 174 events per year. These events primarily affect agricultural and urban/residential areas, which are mostly prevalent in low-elevation regions (0–500 meters above sea level), and are closely associated with flat terrain. Temporally, PB events occur

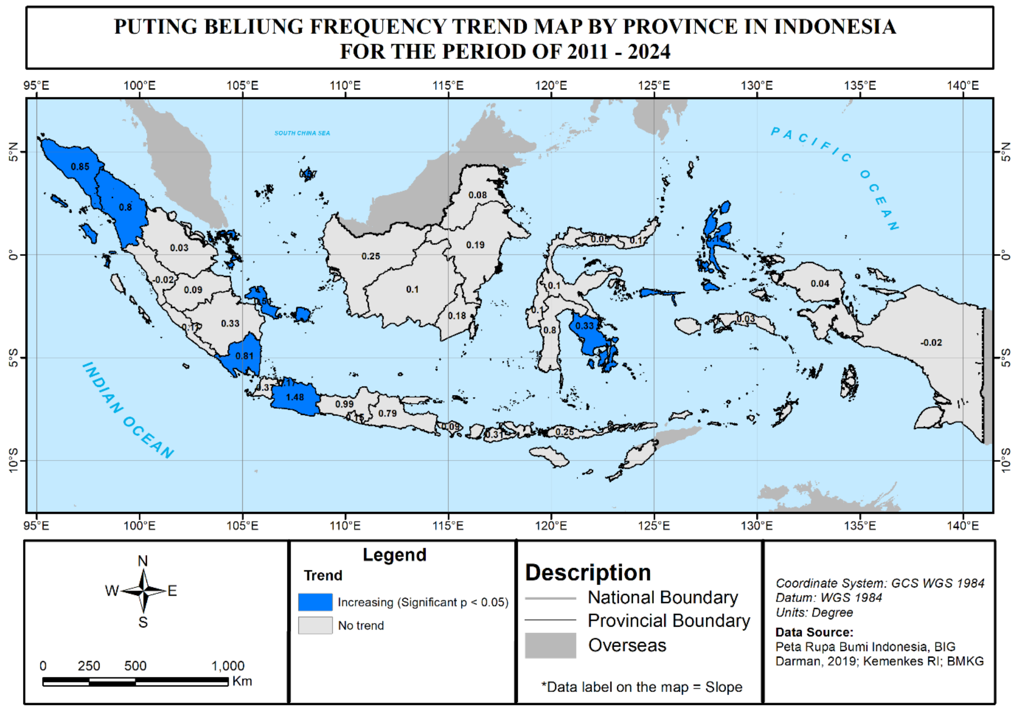

Figure 14. PB Frequency Trend Map by Province in Indonesia for the Period of 2011-2024. Blue Shade Represents Statistically Significant Trends at 95% Confidence Level, Labels on Map Represent Trend Magnitude

most frequently in January, March, and November, which is in line with Indonesian monsoonal and transitional seasons, and they typically peak in the afternoon (13:00–15:00 local time). It is important to note that there may be reporting bias in the less populated eastern regions, as the spatial distribution of PB events closely mirrors population density.

The Mann-Kendall trend analysis shows a statistically significant national increase in PB frequency, with an average annual rise of approximately 12 events. Subsequently, a notable increases are observed in 8 provinces, namely Aceh, North Sumatra, Riau Islands, Bangka Belitung Islands, Lampung, West Java, Southeast Sulawesi, and North Maluku, some of which experience approximately 1.5 additional events per year. These results indicate an escalating risk of PB events in Indonesia, particularly in densely populated provinces undergoing rapid urbanization. To address the growing threat of PB events amid ongoing climate and land-use changes, this research highlights the importance of adaptive land-use planning, the development of early warning systems, and targeted disaster mitigation strategies, specifically in agricultural plains and expanding urban areas.

Future research will explore the relationship between the spatiotemporal patterns of PB events in Indonesia and key meteorological parameters that are critical to their genesis. A comprehensive analysis of vertical wind shear at low (0–3 km) and medium (0–6 km) levels, low-level relative humidity, Convective Available Potential Energy (CAPE), skin temperature, and other relevant atmospheric variables is expected to provide deeper insights into the conditions conducive to PB formation. Another important direction for future research will be to examine the relationship between changing trends in PB events and PB days in the context of climate change.

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